

## Suppressed $B$ Decays at CDF

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We present two recent results obtained by the CDF collaboration at the Tevatron collider. New Cabibbo suppressed  $B_s^0$  decay modes have been observed using  $5.9 \text{ fb}^{-1}$  of data:  $B_s^0 \rightarrow J/\psi K_S^0$  and  $B_s^0 \rightarrow J/\psi K^{*0}$ . We report also on measurement of the ratios of the branching ratios (BR) of the new modes to those of the  $B^0$ -meson to the same final states:

$$\text{BR}(B_s^0 \rightarrow J/\psi K^{*0}) / \text{BR}(B^0 \rightarrow J/\psi K^{*0}) = 0.062 \pm 0.009(\text{stat.}) \pm 0.025(\text{sys.}) \pm 0.008(\text{frag.})$$

and

$$\text{BR}(B_s^0 \rightarrow J/\psi K_S^0) / \text{BR}(B^0 \rightarrow J/\psi K_S^0) = 0.041 \pm 0.007(\text{stat.}) \pm 0.004(\text{sys.}) \pm 0.005(\text{frag.}).$$

Then we discuss the first polarization measurement in a charmless  $B_s^0$  decay in two light vector mesons,  $B_s^0 \rightarrow \phi\phi$ , using  $2.9 \text{ fb}^{-1}$  of data. An angular analysis of the final state particles allows CDF to determine a longitudinal polarization fraction  $f_L = 0.348 \pm 0.041(\text{stat.}) \pm 0.021(\text{syst.})$ , which is inconsistent with naïve expectations based on the V-A nature of weak currents and confirms the pattern of lower than expected longitudinal polarization fraction in  $b \rightarrow s$  penguin dominated  $B \rightarrow VV$  decays. Finally, an updated measurement of the ratio of  $B_s^0 \rightarrow \phi\phi$  BR to that of the reference  $B_s^0 \rightarrow J/\psi\phi$  mode is also presented:

$$\text{BR}(B_s^0 \rightarrow \phi\phi) / \text{BR}(B_s^0 \rightarrow J/\psi\phi) = [1.78 \pm 0.14(\text{stat.}) \pm 0.20(\text{syst.})] \cdot 10^{-2}.$$

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## 1. Introduction

The Tevatron collider has provided in the last decade an impressive amount of  $p\bar{p}$  collision data that the two collaborations, CDF and D0, have very fruitfully exploited. In particular large, samples of fully reconstructed  $B_s^0$  decays have been collected allowing crucial progress on  $B_s^0$  mixing, lifetime, decay width difference  $\Delta\Gamma_s$  as well as the observation of a large number of decay modes. We will review here two recent results from the CDF experiment: the first observation of the Cabibbo suppressed  $B_s^0 \rightarrow J/\psi K_S^0$  and  $B_s^0 \rightarrow J/\psi K^{*0}$  decay modes and measurement of their branching ratio (BR) [1], and the first angular analysis of charmless  $B_s^0 \rightarrow \phi\phi$  decay for the determination of polarization amplitudes [2].

Important characteristics of the CDF II detector [3] that are worth to be mentioned in connection to these two measurements are the trigger and charged track reconstruction capabilities. A dimuon trigger with a  $p_T$  threshold as low as 1.5 GeV/c and  $|\eta| < 1$  is used for  $B \rightarrow J/\psi X$  modes. The trigger on displaced vertex with online measurement of impact parameter of charged tracks [4] allows the collection of hadronic decay modes like  $B_s^0 \rightarrow \phi\phi$ . The charged particles in the pseudorapidity range  $|\eta| \lesssim 1$  are reconstructed by a silicon microstrip vertex detector and a drift chamber, providing excellent resolution on  $B$ -meson decay length ( $30\mu\text{m}$ ) and mass, typically about 10 MeV/ $c^2$  for  $B \rightarrow J/\psi X$  modes, that are crucial for the observation of rare  $B_s^0$  modes.

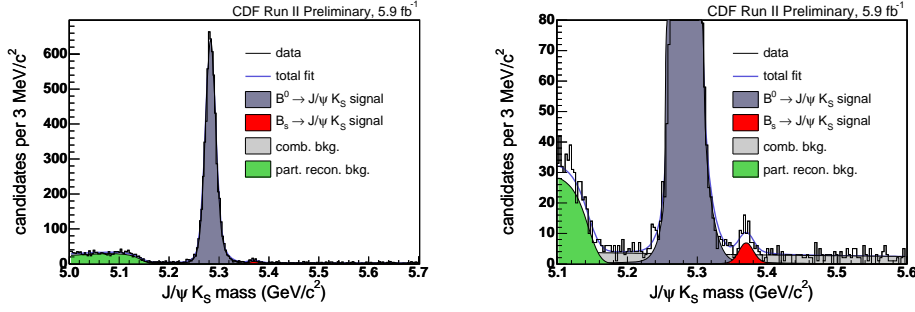
## 2. Observation of $B_s^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi K^{*0}$

The  $B^0 \rightarrow J/\psi K_S^0$  and  $B^0 \rightarrow J/\psi K^{*0}$  decays are celebrated "golden" modes where the greatly dominant amplitude is a Cabibbo favoured tree thus providing a crucial and theoretically clean determination of  $\sin(2\beta)$ . Among the residual theoretical uncertainty, which may become important at the next generation flavor experiments, there are those related to the subleading penguin amplitude which is suppressed by  $O(\lambda^2)$ , where  $\lambda = \sin(\theta_c) \sim 0.2$ , with respect to the tree one. A different ratio between tree and penguin is expected, on the other hand, in the  $B_s^0 \rightarrow J/\psi K_S^0$  and  $B_s^0 \rightarrow J/\psi K^{*0}$  decays. For these modes the tree and penguin amplitudes enter both at order  $O(\lambda)$ . Consequently we expect a decay rate relative to the  $B^0$  ones of order  $O(\lambda^2) \sim 5 - 10\%$ . Moreover, by measuring both the rate and the CP violation in the  $B_s^0 \rightarrow J/\psi K_S^0$  mode, theoretical uncertainties on  $\sin(2\beta)$  due to penguin pollution will be reduced to a fraction of a degree [5]. Similar consideration apply to the study of  $B_s^0 \rightarrow J/\psi K^{*0}$  to constrain theoretical uncertainties in the extraction of  $\sin(2\beta_s)$  from  $B_s^0 \rightarrow J/\psi\phi$  decays [6].

The data used for this measurement corresponds to an integrated luminosity of  $5.9\text{ fb}^{-1}$ . We derive the ratios of branching ratios of  $B_s^0 \rightarrow J/\psi K_S^0$  and  $B_s^0 \rightarrow J/\psi K^{*0}$  to the reference  $B^0$  decays using the relation:

$$\text{BR}(B_s^0 \rightarrow J/\psi K) / \text{BR}(B^0 \rightarrow J/\psi K) = A_{rel} \times f_d / f_s \times N(B_s^0 \rightarrow J/\psi K) / N(B^0 \rightarrow J/\psi K),$$

where  $K$  represents  $K_S$  or  $K^*$ . By measuring the ratio of the number of  $B^0$  and  $B_s^0$  decays from data and the relative acceptance,  $A_{rel}$ , between the  $B^0$  and  $B_s^0$  modes from Monte Carlo simulation (MC), a measurement of  $\text{BR}(B_s^0 \rightarrow J/\psi K) / \text{BR}(B^0 \rightarrow J/\psi K)$  is extracted using the ratio of fragmentation fractions  $f_s / f_d$ .



**Figure 1:** Invariant mass for selected  $B \rightarrow J/\psi K_S^0$  candidates with fit (left). Enlarged version of the same plot showing the  $B_s^0$  signal region in greater detail (right).

The event selection in the  $B^0 \rightarrow J/\psi K^*$  analysis is optimized by maximizing  $S/(1.5 + \sqrt{B})$  [7] in a simultaneous four-dimensional scan over four discriminating quantities:  $\pi p_T$ ,  $K p_T$ , transverse decay length  $L_{xy}$  and  $B$ -vertex fit probability. To extract the  $B^0$  and  $B_s^0$  signal yields a likelihood fit to the invariant mass distribution is performed. The signal shape is modeled with three Gaussians template obtained from a fit to a simulated  $B^0$  sample. The  $B_s^0$  template used in the fit is identical to  $B^0$  template, except for a shift of 86.8 MeV/c<sup>2</sup> in the mean value of the three Gaussians, corresponding to the mass difference between  $B_s^0$  and  $B^0$  [8]. The backgrounds considered in this analysis are combinatorial background, partially reconstructed background and  $B_s^0 \rightarrow J/\psi \phi$  decay. The combinatorial background is modeled with an exponential function. The partially reconstructed one, fitted with an ARGUS function [9], is due to five-body decay with a  $\pi$ ,  $K$ , or  $\gamma$  not reconstructed. Finally, a two Gaussians template, extracted from simulation, is used to model the  $B_s^0 \rightarrow J/\psi \phi$  background, with a normalization constrained by data. The yields for  $B^0$  and  $B_s^0$  modes are respectively  $9530 \pm 110$  and  $151 \pm 25$ . The statistical significances of the  $B_s^0 \rightarrow J/\psi K^{*0}$  signal is  $8.0\sigma$ . The systematic uncertainty is dominated by the combinatorial background contribution, with a relative uncertainty for the  $B^0$  to  $B_s^0$  ratio of 31.4%. Other sources of systematic uncertainty are the signal modeling (4.4%), and  $B_s^0 \rightarrow J/\psi \phi$  contribution (1.3%).

For the observation of the  $B_s^0 \rightarrow J/\psi K_S^0$  a Neural Network (NN) based multivariate classifier is used to further reduce combinatorial background. In order to train the NN, simulated  $B_s^0$  MC events are used as signal. Data from the upper side band in the  $B_s^0$  candidate invariant mass distribution, well separated from the signal region, are used as a background data sample. A likelihood fit similar to the one described before is performed to the invariant mass distribution to extract the yield of the  $B^0 \rightarrow J/\psi K_S^0$  and  $B_s^0 \rightarrow J/\psi K_S^0$  signals. From the fit, shown in Fig. 1, the yields of the  $B^0$  and  $B_s^0$  signal are determined to be  $5954 \pm 79$  and  $64 \pm 14$ , respectively. The statistical significances of the  $B_s^0 \rightarrow J/\psi K_S^0$  signal is  $7.2\sigma$ . In this case the relative uncertainties for the ratio of yields are 5.6% from the combinatorial background contribution, 5.6% from the combinatorial background modeling, 4.6% from the signal modeling.

To determine the  $\text{BR}(B_s^0 \rightarrow J/\psi K)/\text{BR}(B^0 \rightarrow J/\psi K)$ , a correction of 1% and 5% for the ratio of acceptance is obtained from simulation respectively for the  $J/\psi K_S^0$  and  $J/\psi K^{*0}$  case. The  $B_s^0$  and  $B^0$  lifetimes, B hadron  $p_T$  spectrum and polarization, this last one only for the  $B_s^0 \rightarrow J/\psi K^{*0}$

analysis, are considered as a source of systematic uncertainty in the efficiency correction. The most recent CDF measurement [10] of  $f_s/(f_u + f_d) \times Br(D_s \rightarrow \phi\pi)$  is combined with the actual PDG value [8] for  $Br(D_s \rightarrow \phi\pi)$ , to extract  $f_s/f_d = 0.269 \pm 0.033$ . We can thus estimate:

$$\begin{aligned} BR(B_s^0 \rightarrow J/\psi K^{*0})/BR(B^0 \rightarrow J/\psi K^{*0}) &= 0.062 \pm 0.009(stat.) \pm 0.025(sys.) \pm 0.008(frag.) \\ BR(B_s^0 \rightarrow J/\psi K_S^0)/BR(B^0 \rightarrow J/\psi K_S^0) &= 0.041 \pm 0.007(stat.) \pm 0.004(sys.) \pm 0.005(frag.). \end{aligned}$$

This confirms the order of magnitude estimate,  $O(\lambda^2)$ , for this ratio given above.

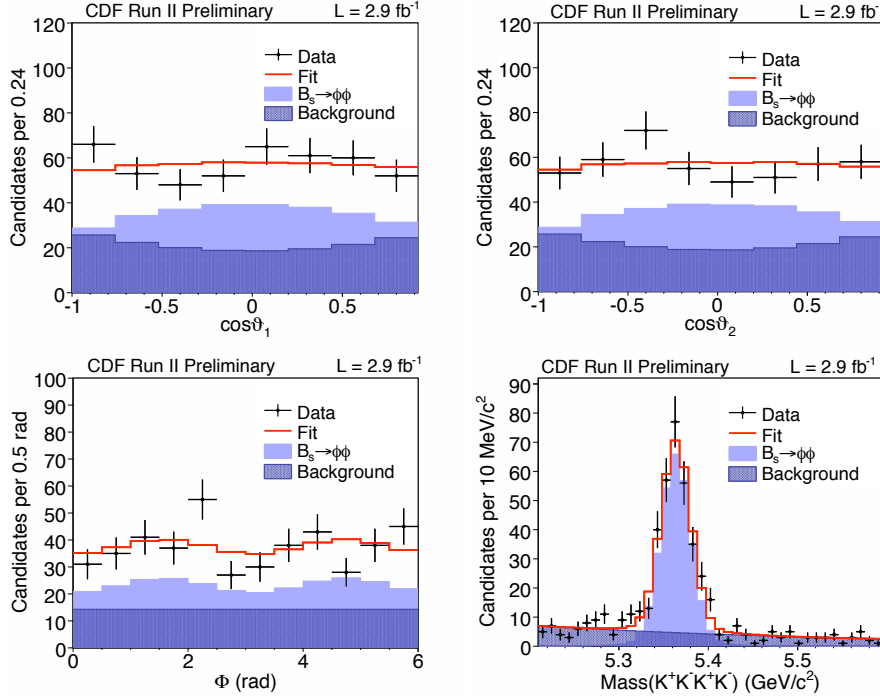
### 3. $B_s^0 \rightarrow \phi\phi$ Polarization Measurement

The  $B_s^0 \rightarrow \phi\phi$  belongs to a particular class,  $B_s^0 \rightarrow VV$ , of decays in a pair of  $J=1$  mesons which are in a superposition of CP eigenstates. It will be used to constrain new physics contribution to  $B_s^0$  mixing phase through a measurement of time dependent CP violation. Three independent amplitudes govern  $B_s^0 \rightarrow VV$  decays, corresponding to the possible polarizations of the final state mesons. It is thus attractive to test the theoretical predictions for these polarization amplitudes [11, 12, 13]. Evidence for the  $B_s^0 \rightarrow \phi\phi$  process has been reported by CDF with low statistics [14]. We discuss here the first measurement of polarization amplitudes in this decay and an updated measurement of the branching ratio using  $2.9 \text{ fb}^{-1}$ . The  $B_s^0 \rightarrow \phi\phi$  decay proceeds through a  $b \rightarrow s\bar{s}s$  quark level process, and, in the Standard Model (SM), the dominant diagram is the  $b \rightarrow s$  penguin. The same penguin amplitude is involved in several processes which have shown several discrepancies with the SM predictions. In particular, both SM and new physics interpretations have been considered to explain the lack of dominant longitudinal polarization component for several penguin dominated  $B \rightarrow VV$  decay modes [15]. Measurements of polarization amplitudes in new modes, including  $B_s^0 \rightarrow \phi\phi$  decays, have been proposed [16] to resolve this issue. We study also  $B_s^0 \rightarrow J/\psi\phi$  decays in the same dataset, use this mode as a normalization for the  $B_s^0 \rightarrow \phi\phi$  BR measurement and extract  $B_s^0 \rightarrow J/\psi\phi$  polarization amplitudes as a cross check of the main  $B_s^0 \rightarrow \phi\phi$  result.

Event selection is the same for both BR and polarization measurement and is described in detail elsewhere [17]. The invariant mass of the selected  $B_s^0 \rightarrow \phi\phi$  candidates is shown in Fig. 2 along with the projection of the likelihood fit described in the following. Two sources of background are expected in the  $B_s^0$  signal region: combinatorial background and  $B^0 \rightarrow \phi K^{*0}$  reflection with the wrong assignment of a kaon mass to the  $K^{*0}$  decay pion. Similar consideration apply for the  $B_s^0 \rightarrow J/\psi\phi$  case where  $B^0 \rightarrow J/\psi K^{*0}$  constitute the only expected reflection component. We estimate a contribution of  $f_{B^0 \rightarrow J/\psi K^{*0}} = (4.19 \pm 0.93)\%$  and  $f_{B^0 \rightarrow \phi K^{*0}} = (2.7 \pm 1.0)\%$  under respectively the  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \phi\phi$  signals and fit the total number of signal decays as  $N_{\phi\phi} = 295 \pm 20 \pm 12$  and  $N_{\psi\phi} = 1766 \pm 48 \pm 41$  where the first uncertainty is statistical and the second is systematic and is evaluated using alternative signal and background models.

To extract the  $B_s^0 \rightarrow \phi\phi$  decay rate first the measurement of the branching ratio ratio to the  $B_s^0 \rightarrow J/\psi\phi$  mode is performed by correcting for the relative detection efficiency for the two decays:  $BR(B_s^0 \rightarrow \phi\phi)/BR(B_s^0 \rightarrow J/\psi\phi) = [1.78 \pm 0.14(stat.) \pm 0.20(syst.)] \cdot 10^{-2}$ . We then derive  $BR(B_s^0 \rightarrow \phi\phi) = [2.40 \pm 0.21(stat.) \pm 0.27(syst.) \pm 0.82(BR)] \cdot 10^{-5}$ , adopting the  $BR(B_s^0 \rightarrow J/\psi\phi)$  from ref. [18], corrected for the current measurements [8] of  $f_s/f_d$ <sup>1</sup>. The dominant systematic

<sup>1</sup>We actually use:  $BR(B_s^0 \rightarrow J/\psi\phi) = (1.35 \pm 0.46) \cdot 10^{-3}$



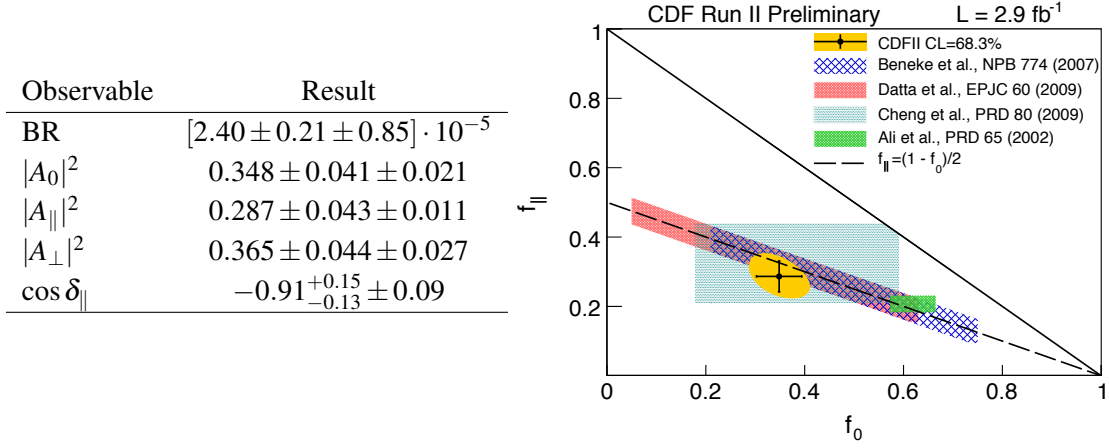
**Figure 2:**  $B_s^0 \rightarrow \phi\phi$  candidate mass and angular distribution with overlaid fit result for signal and background.

uncertainty, labeled (BR), originate from the  $\text{BR}(B_s^0 \rightarrow J/\psi\phi)$  uncertainty alone. This result is in agreement and supersedes our previous measurement[14] and represents a substantial improvement in the statistical uncertainty; it is as well compatible with recent theoretical predictions [11, 12, 13].

The angular distribution of the  $B_s^0 \rightarrow \phi\phi$  decay products can be described using the helicity variables,  $\vec{\omega} = (\cos \vartheta_1, \cos \vartheta_2, \Phi)$ , where  $\vartheta_i$  is the angle between the direction of the  $K^+$  from each  $\phi \rightarrow K^+K^-$  and the direction opposite the  $B_s^0$  in the vector meson rest frame, while  $\Phi$  is the angle between the two resonance decay planes. The total decay amplitude can be decomposed in three complex amplitudes  $H_\lambda$  corresponding to the vector helicity  $\lambda = 0, \pm 1$ ; we use their linear combinations which give the polarization amplitudes<sup>2</sup>:  $A_0 = H_0$ ,  $A_\parallel = (H_+ + H_-)/\sqrt{2}$  and  $A_\perp = (H_+ - H_-)/\sqrt{2}$ . The differential decay rate can be expressed as  $\frac{d^4\Gamma}{dt d\vec{\omega}} \propto \sum_{i=1}^6 K_i(t) f_i(\vec{\omega})$  where the  $K_i(t)$  terms account for the exponential decay and the time evolution of the  $B_s^0$  state due to mixing and decay width differences  $\Delta\Gamma_s$  while the  $f_i(\vec{\omega})$  are functions of the helicity angles only. We measure the untagged decay rate integrated in time and neglect the  $B_s^0$  mixing phase (tiny in the SM) and assume no direct CP violation. The differential decay rate then depends on the polarization amplitudes at  $t = 0$  and on the light and heavy  $B_s^0$  mass-eigenstate lifetimes,  $\tau_L$  and  $\tau_H$  respectively, as follows:

$$\begin{aligned} \frac{d^3\Gamma}{d\vec{\omega}} \propto & \tau_L (|A_0|^2 f_1(\vec{\omega}) + |A_\parallel|^2 f_2(\vec{\omega}) + \\ & + |A_0||A_\parallel| \cos \delta_\parallel f_3(\vec{\omega})) + \tau_H |A_\perp|^2 f_3(\vec{\omega}), \end{aligned} \quad (3.1)$$

<sup>2</sup>The polarization amplitudes are normalized so that the following condition holds:  $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$ .



**Figure 3:**  $B_s^0 \rightarrow \phi\phi$  experimental results with stat. and syst. uncertainties (left panel), comparison to recent theory predictions (right panel).

where  $\delta_{\parallel} = \arg(A_0^* A_{\parallel})$ . and

$$\begin{aligned}
 f_1(\vec{\omega}) &= 4\cos^2 \vartheta_1 \cos^2 \vartheta_2, & f_2(\vec{\omega}) &= \sin^2 \vartheta_1 \sin^2 \vartheta_2 (1 + \cos 2\Phi), \\
 f_3(\vec{\omega}) &= \sin^2 \vartheta_1 \sin^2 \vartheta_2 (1 - \cos 2\Phi), & f_5(\vec{\omega}) &= \sqrt{2} \sin 2\vartheta_1 \sin 2\vartheta_2 \cos \Phi.
 \end{aligned}$$

We perform an unbinned maximum likelihood fit to the reconstructed mass  $m$  of the  $B_s^0$  candidates and the helicity variables in order to measure the polarization amplitudes. The mass distribution is used in the fit to discriminate the signal from the background. The identification of the two  $\phi$  as  $\phi_1$  and  $\phi_2$  to define the angles  $\vartheta_1$  and  $\vartheta_2$  is randomly implemented in order to satisfy the Bose symmetry under indexes exchange  $1 \leftrightarrow 2$ . The likelihood for each candidate is defined as  $\mathcal{L}_i = (1 - f_b) \mathcal{P}_s(m_i, \vec{\omega}_i | \vec{\xi}_s) + f_b \mathcal{P}_b(m_i, \vec{\omega}_i | \vec{\xi}_b)$ , where  $f_b$  is the fraction of the background and  $\mathcal{P}_j(m_i, \vec{\omega}_i | \vec{\xi}_j)$  are the probability density function (PDF) for the  $B_s^0 \rightarrow \phi\phi$  signal ( $j = s$ ) and background ( $j = b$ ) components which depend on the fitting parameters,  $\vec{\xi}_s$  and  $\vec{\xi}_b$  respectively. Both the signal and the background PDF are the product of a mass PDF and an angular one. The signal mass component for both signal and background has been already described. Fixing  $\tau_L$  and  $\tau_H$  to the world average values [8], the angular PDF for the signal is given by Eq. 3.1 multiplied by an acceptance factor; the latter is implemented as a three-dimensional histogram representing the probability to find an event at each position of the  $\vec{\omega}$  space. The angular acceptance is derived from a MC simulation of the  $B_s^0 \rightarrow \phi\phi$  decay, generated averaging over all possible spin states of the decay products. We use a purely empirical parameterization derived by analysing the angular distributions in the mass sidebands to model the background angular PDF. The fitter is extensively tested using simulated samples with a variety of input parameters. A further check is performed by repeating the same measurement for the  $B_s^0 \rightarrow J/\psi\phi$  events collected with the same displaced vertex trigger as  $B_s^0 \rightarrow \phi\phi$ ; we find  $|A_0|^2 = 0.534 \pm 0.019(\text{stat})$  and  $|A_{\parallel}|^2 = 0.220 \pm 0.025(\text{stat})$ , in very good agreement with CDF and D0 measurements [19].

Fit projections on the angular variables and the results for the polarization observables compared to recent theory calculations are shown in Fig. 2 and Fig. 3. Several sources of systematic uncertainty are considered. We account for the physics background effects through simulated samples. We consider the  $B^0 \rightarrow \phi K^{*0}$  decay, the resonant  $B_s^0 \rightarrow \phi f_0(980)$  decay and the decay  $B_s^0$  to  $\phi$



plus a non-resonant kaon pair, whose fractions are normalized to the signal yield in analogy with similar  $B^0$  decays. Assuming up to 4.6% contamination of  $B_s^0 \rightarrow \phi f_0$  and 0.9% of  $B_s^0 \rightarrow \phi(K^+K^-)$  we estimate a 1.5% systematic uncertainty from backgrounds unaccounted for. Possible biases introduced by the time integration are examined with MC simulation: they are induced by the dependence of the angular acceptance on  $\Delta\Gamma_s$  and by a non-uniform acceptance with the  $B_s^0$  proper decay time introduced by the displaced track trigger; the assigned systematic (1%) is the full shift expected in central value, assuming a value for  $\Delta\Gamma_s$  equal to the world average plus one standard deviation. We consider the propagation of  $\tau_{L(H)}$  uncertainties to the polarization amplitudes (1%). We have also verified that the impact of a sizeable CP-violating phase in  $B_s^0$  mixing would be negligible on polarization observables. Combinatorial background parametrization and angular acceptance give minor contributions to systematic uncertainties.

In conclusion for  $B_s^0 \rightarrow \phi\phi$  we find a significantly suppressed longitudinal fraction  $f_L = |A_0|^2 = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst})$ , that is found to be even smaller than in other  $b \rightarrow s$  penguin  $B \rightarrow VV$  decays [8]. This result is in agreement, within uncertainties, with predictions [11, 13] based on QCD factorization, but seems to contradict others [12]. It implies the hierarchy  $H_0 \simeq H_+ \gg H_-$  in polarization amplitudes, possibly induced by a large penguin annihilation contribution [15, 16].

## References

- [1] CDF note 10240, <http://www-cdf.fnal.gov/physics/new/bottom/100708.blessed-BsJpsiK>
- [2] CDF note 10120, [http://www-cdf.fnal.gov/physics/new/bottom/100304.blessed-Bsphi phi\\_amplitudes](http://www-cdf.fnal.gov/physics/new/bottom/100304.blessed-Bsphi phi_amplitudes)
- [3] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71**, 032001 (2005).
- [4] W. Ashmanskas *et al.*, Nucl. Instrum. Meth. A **518**, 532 (2004).
- [5] K. De Bruyn, R. Fleischer and P. Koppenburg, arXiv:1010.0089 [hep-ph].
- [6] S. Faller, R. Fleischer and T. Mannel, Phys. Rev. D **79**, 014005, (2009).
- [7] G. Punzi, arXiv:physics/0308063.
- [8] Particle Data Group, Phys. Lett. **B667**, 1 (2008).
- [9] ARGUS Collaboration, H. Albrecht, Phys. Lett. B **241**, 278, (1990).
- [10] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **77**, 072003, (2008).
- [11] M. Beneke, J. Rohrer and D. Yang, Nucl. Phys. B **774**, 64 (2007) [arXiv:hep-ph/0612290].
- [12] A. Ali, *et al.* Phys. Rev. D **76**, 074018 (2007) [arXiv:hep-ph/0703162].
- [13] H. Y. Cheng and C. K. Chua, Phys. Rev. D **80**, 114026 (2009) [arXiv:0910.5237 [hep-ph]].
- [14] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **95**, 031801, 2005.
- [15] A. Datta *et al.*, Phys. Rev. D **76** (2007) 034015 [arXiv:0705.3915 [hep-ph]].
- [16] A. Datta *et al.*, Eur. Phys. J. C **60**, 279 (2009) [arXiv:0802.0897 [hep-ph]].
- [17] CDF note 10064, <http://www-cdf.fnal.gov/physics/new/bottom/090618.blessed-Bsphi phi2.9/>
- [18] F. Abe *et al.* [CDF Collaboration], Phys. Rev. D **54**, 6596 (1996).
- [19] CDF collaboration, Phys. Rev. Lett. **100**, 121803 (2008); D0 Collaboration, Phys. Rev. Lett. **102**, 032001 (2009).